Cherry damage and the spatial distribution of European earwigs, (*Forficula auricularia* L.) in sweet cherry trees

Short Title: European earwig damage to sweet cherry

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Abstract

BACKGROUND: The European earwig, *Forficula auricularia* is an invasive insect pest found in many temperate regions of the world. Despite being well known predators, they are considered pests in sweet cherry though this has never been empirically tested. Our aim was to quantify the relationship between damaged cherry fruit and earwig population size, cherry bunch size and earwig distribution in cherry tree canopies in the cherry varieties Ron's Seedling, Lewis, Sweet Georgia, and Lapin.

RESULTS: Significant differences in earwig damage type and frequency were observed between varieties with earwig exclusion significantly reducing damage by 21% in Lapin and 34% in Ron's Seedling. Earwigs were strongly aggregated within cherry bunches, with greater numbers and damage observed in larger bunch sizes in all varieties except Ron's Seedling where stem damage was independent of bunch size. In Ron's Seedling, cherry stems were 40x more likely to be damaged than Lewis stems and Lewis fruit two times more likely to be damaged than Ron's Seedling fruit. Sweet Georgia fruit were 4.5 times and stems 5 times more likely to be damaged than in Lapin. No predictive relationship between cherry damage levels and earwig numbers either within the tree canopies or within monitoring traps could be determined.

CONCLUSION: European earwigs may have a significant economic impact to sweet cherry production. The nature of this impact differs between cherry varieties and severity is strongly

influenced by factors including bunch size. However, why damage differs between varieties remains unknown and warrants further investigation if the impact of earwigs to sweet cherry production is to be minimised.

Keywords: Dermaptera, aggregation, monitoring, *Prunus avium*

1 INTRODUCTION

The European earwig, *Forficula auricularia* L. (Dermaptera: Forficulidae), is a subsocial, invasive insect species found in many temperate regions around the world.[1] During its seasonal activity window *F. auricularia* exhibit a strong thigmotactic response, aggregating in large numbers under rocks, logs and within tree canopies aided by the use of a putative aggregation pheromone.[2-5] Despite their invasive nature, earwigs have been shown to be useful biological control agents against numerous insect pests in apple[6-8], orange[9], and kiwi fruit[10] orchards, vineyards[11] and hop gardens.[12] Indeed, due to their predatory nature, earwigs have also been assessed as a potential biological control agent for spotted-wing Drosophila (*Drosophila suzukii*) in soft fruit crops.[13, 14] However, due to their omnivorous feeding habit coupled with their aggregation behaviours, earwigs have also been long considered a nuisance in urban settings[1, 5] as well as a damaging pest in many vegetable crops[15], grapes[16], and stone fruits including nectarines[17] and apricots[18, 19], where earwigs have been reported to damage up to 40% of some harvests.[20]

In sweet cherries (*Prunus avium* L.), earwigs are regarded as a pest reportedly damaging fruit and are a potential issue in post-harvest packing, export and biosecurity.[21] The impact *F. auricularia* has on cherry production is currently unknown, although earwig feeding damage has been reported on cherry leaves, fruit buds, pedicels (henceforth referred to as stem) and fruit in both Australia[21, 22] and in the U.S.A.[23] This grey literature states earwig feeding results in shallow, irregular holes in the cherry fruits, which may also become infected with secondary fungal infections.[24]

Despite its assumed pest status, there has been no empirical research undertaken quantifying the impact earwigs have on cherry production or any action thresholds developed to determine insecticide usage in cherries. Many university and governmental agricultural extension documents state that *F. auricularia* is a pest in cherries and provides chemical management strategies for their control.[21, 24-27] It is therefore essential that any impact that earwigs may have on cherry production be quantified to determine whether these anecdotal reports are accurate, as broad-spectrum insecticide applications remain the primary method of earwig control. Furthermore, a greater understanding is needed of how earwig daytime aggregation behaviours are exhibited within cherry tree canopies, and how these behaviours impact on any putative fruit damage if monitoring programs are to be developed and implemented as part of Integrated Pest Management (IPM) programs.

The study firstly aimed to examine how intra-tree factors including cherry bunch size, cherry bunch position along the limb and limb aspect influence earwig location within cherry tree canopies. We also aimed to quantify cherry fruit and stem damage attributable to earwig feeding. Secondly, we examined how the level of damage varied according to both the intra-tree factors and the cherry varieties Lapin, Lewis, Ron's Seedling and Sweet Georgia in two regions of Australia. Finally, we explored whether earwig traps on trunks at harvest can be used to predict the level of earwig damage found in cherry trees.

2 MATERIALS AND METHODS

2.1 Experimental study sites

To assess earwig cherry damage, exclusion and cherry bunch size experiments were undertaken in three cherry orchards across New South Wales (NSW) and Tasmania (TAS) Australia, all of which were known to contain large earwig populations (Table 1). In Young NSW, three experimental sites across two properties were selected. On the first property (34˚ 18.296′ S 148˚ 21.042′ E) two blocks were selected. The first block consisted solely of Ron's Seedling (RS1). The second block consisted of alternating plantings of Ron's Seedling and Lewis cherry trees (RS/LW). On the second property in Young, a single block of Ron's Seedling was selected (RS2: 34˚ 26.877′ S, 148˚ 18.974′ E). In Grove Tasmania, one block of Lapin and one neighbouring block of Sweet Georgia were selected from a National Association for Sustainable Agriculture (NASAA) certified organic orchard (42˚ 59.755' S, 147˚ 4.328' E). All cherry trees were pruned to a vase system. No chemical insecticide applications were applied over the experimental period. Row orientation, row and tree spacing, tree age and ground cover all varied between blocks (Table 1).

2.2 Earwig exclusion and mapping earwig, cherry bunch size and cherry damage within the canopy

Three blocks (RS1, RS2 and Lapin) were used for this experiment (Table 1). Three weeks prior to fruit harvest, 20 trees per block were randomly selected with one limb from each tree designated as an exclusion limb, thereby controlling for any damage that may occur in the absence of earwigs. These bands were anticipated to have limited disturbance on other insect fauna within the tree canopies as no other crawling insect species are known reside within Australian cherry tree canopies[28]. An exclusion band was applied to each exclusion limb by wrapping 5 cm wide duct tape around the limb's base and then smearing Tanglefoot® Insect Barrier (Contech Electronics Inc.) over the tape to prevent earwigs from accessing the developing fruit on the control limbs. Any earwigs and damaged fruit found within cherry bunches on this exclusion limb were removed at this time. To monitor earwig numbers at harvest an earwig trap consisting of a rolled piece of corrugated cardboard (8.5 cm x 9 cm), was tied with garden twine (Zenith, REA 0060) to each of the 20 tree trunks 30 cm above ground level. To assess the efficacy of the exclusion band another earwig trap was tied above each limb's exclusion band. The traps on the exclusion limbs were checked for earwigs with any earwigs released at the base of each tree. Once checked, the traps on these limbs were replaced. The exclusion limbs were also reassessed for both damaged cherry fruit and earwigs that may have been residing within the fruit bunches, both of which were removed from the exclusion limbs.

Cherry damage and earwig data were recorded 1-2 days prior to cherry harvest (Table 1). At this time, the number of earwigs found within the trunk and exclusion limb traps, their sex and life stage, number of cherry bunches per limb, number of cherries per bunch, damaged cherries per bunch, damage type and any earwigs found within each bunch were recorded on both the exclusion limbs and four other limbs selected from each of the four cardinal points (North, South, East and West) of each tree. Earwig damage type was characterised as either fruit damage (chewing damage to the cherry fruit) or stem damage (chewing damage to the cherry fruit stem). The position of each cherry bunch along the limb was recorded as either in the lower, middle or terminal third of each limb and as either on the main limb, fork shaped limb or on a small side branch.

2.3 Cherry damage in relation to cherry variety, bunch size and earwig location

To assess the effect that cherry bunch size and cultivar have on the presence of earwigs within bunches and subsequent cherry damage, 40 trees were randomly selected from the interplanted RS/ LW block and 20 trees randomly selected from the Sweet Georgia block (Table 1). Due to difficulties finding Lapin cherry blocks with sufficient earwig populations and fruit load during the 2011/12 season, the Lapin cherry bunch, cherry damage and earwig data from the four cardinal limbs of the exclusion experiment were used to generate the data for the Lapin cultivar. Three weeks prior to cherry harvest, cardboard earwig traps as previously described in the exclusion experiment were tied to the trunk of each tree with garden twine 30 cm from the ground surface. To ensure a broad range of bunch sizes were selected, a maximum of six of each fruit bunch size (1-2, 3-6, 7-12, 13-18, 19-25 and 25+

fruits per bunch) were randomly selected within each tree. Again, all earwig, cherry bunch and damage data were recorded a maximum two days prior to harvest as previously described in the exclusion experiment, except for bunch position and limb aspect, which were not recorded.

2.4 Data Analysis

Data from the earwig exclusion experiment collected to examine the influence limb aspect, bunch position along the limb and earwig trunk trap numbers have on the incidence of cherry fruit and stem damage were analysed using logistic regression with a binary logit link. All variables were included in the initial models with any non-significant effects removed to simplify the final model. The relationship between cherry bunch size and earwig numbers found within bunches was also analysed using logistic regression with a log link function for each cultivar. Best regression model fit was assessed using both AIC[29] and Vuong's closeness tests[30] (see Table S1 for all AIC and Vuong statistics) in SAS version 9.2 using the proc countreg procedure and the Vuong macro. Due to the high number of cherry bunches that contained no earwigs, zero inflated models were deemed the more appropriate distributions for statistical analysis. Cherry bunch aspect, bunch position and their interaction were analysed using a generalised linear model in SAS using proc genmod with a zero-inflated Poisson (ZIP) distribution. Due to the low number of damaged fruits in the Ron's Seedling blocks, regression analysis was not possible and contingency table analysis were performed to assess the impact both limb orientation and bunch position has on fruit and stem damage using IBM SPSS Statistics 19 (IBM Corp. 2010).

To investigate the relationship between the number of earwigs found within bunches, cherry cultivar and cherry bunch size, a generalised linear mixed model (GLMM) using a logit link function and orchard as a random variable was used. Vuong and AIC tests were again performed to determine model best fit in SAS with the GLMM performed using proc glimmix. The predictive accuracy of the ZIP models and zero-inflated negative binomial (ZINB) models used to examine the relationship between earwig numbers in bunches and cherry bunch sizes were determined using Nash-Sutcliffe efficiency model coefficients (E) using the 'epiphy' package in R (version 2.15.1) where E ranges from $-\infty$ to 1. An $E = 1$ is deemed a perfect model prediction and an $E \leq 0$ indicates an unacceptable model performance and that the observed mean is a better indicator than the predicted value.[31] Odds ratios of stem and fruit damage on bunch data between the four varieties were determined using a binomial distribution with earwigs per bunch and cultivar as explanatory variables, and tree as a random variable. To compare fruit and stem damage incidence within varieties (within regions), Wilcoxon signed ranks tests were performed and Mann-Whitney U tests used to compare differences between varieties using IBM SPSS Statistics 19 (IBM Corp. 2010).

How the level of earwig aggregation may vary across varying cherry bunch sizes and within tree canopies was assessed using the aggregation parameter, theta (θ).[32] Theta values approaching zero indicate a negative binomial (NB) distribution (earwig aggregation) and values approaching infinity indicate a Poisson distribution (random distribution). To determine the relationship between bunch size and the level of earwig aggregation, θ estimates were calculated for bunches within each cultivar using a sliding scale of 12 cherries i.e. bunches containing 2-14 cherries, 3-15 cherries etc. The aggregation behaviour analysis used only bunches where more than one earwig was present. Confidence intervals were determined for the θ estimates using a bootstrapping procedure in which the data were re-sampled 100 times using the R sample function.

3 RESULTS

3.1. Earwig exclusion and mapping earwig, cherry bunch size and cherry damage within the canopy

3.1.1 Cherry bunch sizes within the tree

Cherry bunch sizes varied significantly in RS1, RS2 and Lapin trees with respect to position of the cherry bunch along the limb and the cardinal direction of the limb (Table 2). In Lapin, where trees were spaced closer together and row orientation was north-west/south-east, larger fruit bunches occurred in limbs on the eastern, western and southern sides of the trees (χ^2 = 16.4, df = 3, P = 0.001) with the largest bunches occurring within the outermost third of all limbs (χ^2 = 7.7, df = 2, P = 0.02). Conversely, in RS1 and RS2 larger bunches occurred on the eastern limbs of the tree (RS1: χ^2 = 18.6, df = 3, P < 0.001; RS2 χ^2 = 17.8, df = 3, P < 0.001). In RS1, bunch size did not vary along the limb (χ^2 = 4.4, df = 2, P = 0.11), however in RS2 larger bunches were observed in the outer third of the eastern and western limbs (χ^2 = 25.9, df = 2, P < 0.001).

3.1.2 Earwig presence in trees

Due to the large number of bunches with no earwigs present, the zero-inflated Poisson (ZIP) was determined to be the best distribution to analyse the number of earwigs residing within cherry bunches (Vuong Z = -2.6, AIC = 843). Cherry damage was significantly reduced by earwig exclusion. Exclusion bands on the Lapin exclusion limbs significantly reduced the number of earwigs found within the cherry bunches where only one earwig was observed in the exclusion limb bunches (χ^2 = 32.4, df = 4, P < 0.001) reducing the level of fruit damage from 6.6% to 0.7% (χ^2 = 59.0, df = 4, P < 0.001) and stem damage from 2% to 0.4% (χ^2 = 324.3, df = 4, P < 0.001). At both RS sites, earwigs were able to circumvent the exclusion bands on some trees. At RS1, 20 earwigs were found in the earwig traps on the exclusion limbs and 48 earwigs in the traps on the exclusion limbs at RS2. Despite this, stem damage at both sites was significantly reduced by ca. 2.5-fold through exclusion (RS1: χ^2 = 16.71, df = 4, P = 0.002; RS2: χ^2 = 24.85, df = 4, P < 0.001). Statistics could not be performed on the Ron's Seedling fruit damage within orchards due to the low number of fruits damaged, however, when the two RS orchards were pooled together there was a significant 3-fold reduction in fruit damage in the exclusion limbs (χ^2 =15.42, df = 4, P = 0.004).

In the non-exclusion limbs, there was no significant difference between the two Ron's Seedling blocks with respect to the overall number of earwigs found within the fruit bunches (χ^2 = 1.8, df = 1, P = 0.06). However, very low earwig numbers were found within the cherry bunches at both sites with a total of 2 earwigs found within all RS1 bunches and 11 earwigs at RS2. Hence, regression modelling of earwig numbers and bunches for RS was not possible. More earwigs were found in RS1 trunk traps than in RS2 (χ^2 = 31.0, df = 1, P < 0.001) with low earwig numbers also evident in traps at both locations (mean ± SEM; RS1: 2.10 ± 0.04 and RS2: 0.55 ± 0.03).

Significant differences were observed between earwig numbers in Lapin and Sweet Georgia trees at the Tasmanian site. Significantly more earwigs were found in Sweet Georgia trunk traps compared to those within the Lapin block (mean ± SEM; Sweet Georgia: 19.75 ± 2.26; Lapin: 16.05 ± 2.25; U = 105106, Z = 4.1, P < 0.001) and over five times as many earwigs were found within Sweet Georgia cherry bunches (mean ± SEM; Lapin 0.41 ± 0.07; Sweet Georgia 2.06 ± 0.29; U = 99027, Z = 8.6, P < 0.001). Nevertheless, numbers in the tree canopy were not high when compared to those found within the trunk traps, averaging 15.6 ± 1.5 earwigs per four limbs or since each Lapin tree possessed an average of 6 limbs, each tree averaged ca. 23.9 ± 2.9 earwigs per tree canopy. Within the interplanted RS/LW block, greater earwig numbers were found within the Lewis tree canopies compared to the Ron's Seedling canopies (mean ± SEM, RS = 0.13 ± 0.05; LW = 0.37 ± 0.06; U = 61112, Z = -4.1, P < 0.001) but not within the trunk traps where more earwigs were found within traps located on the Ron's Seedling trunks compared to those located on the Lewis trunks (mean ± SEM, RS = 2.9 ± 0.83, LW = 2.25 ± 0.51; U = 53403, Z = 4.9, P < 0.001).

3.1.3 Influence of cherry bunch size on earwig numbers

The greatest number of earwigs found aggregating within a cherry bunch was in a Sweet Georgia where 45 earwigs were found within a single bunch of 13 cherries compared to 27 in a Lapin bunch of 15 cherries, 9 earwigs were found in a Lewis bunch of 46 cherries and 12 earwigs in a Ron's Seedling bunch of a 43 cherries (Fig 1).

Both the Vuong (Z = 2.7) and AIC statistics (ZIP AIC = 3135; ZINB AIC = 2507) indicated a zero-inflated negative binomial (ZINB) distribution was the best model fit (see supporting information). In Lapin trees, earwigs aggregated more strongly in tree canopies with higher fruit loads (θ = 0.49, P < 0.001). More earwigs were found in cherry bunches as bunch size increased for both varieties assessed in the exclusion experiment (χ^2 = 214.1, df = 1, P < 0.001) and the four varieties assessed in the bunch size experiment (χ^2 = 47.2, df = 3, P < 0.001, Fig 1). The Nash-Sutcliffe statistic indicates a significant goodness-of-fit in all ZIP regression models developed from bunch experiment data all with $E_f \geq 0.70$.[31]

In Lapin trees, earwig presence within fruit bunches did not relate to either the limb's cardinal direction (χ^2 = 5.0, df = 3, P = 0.17) or bunch position (χ^2 = 1.1, df = 2, P = 0.59). However, the interaction of the two was shown to play a role in earwig residence (χ^2 = 14.5, df = 6, P = 0.03) where more earwigs were found in the larger, outermost bunches (Table 2) at all aspects except on the western side (Fig 2).

The relationship between the aggregation parameter, θ and bunch size indicates earwig residence within cherry bunches was not random, with θ estimates approaching zero at all bunch sizes across all varieties (Fig 3a). Similarly, θ estimates indicated that earwigs found within bunches resided together and were therefore aggregated within the tree canopies (Fig 3b).

3.2 Cherry damage in relation to cherry variety, bunch size and earwig location

Differences were observed between the two Ron's Seedling orchards with respect to fruit and stem damage (stem: $\chi^2 = 4.9$, df = 1, $P = 0.03$, fruit: $\chi^2 = 13.1$, df = 1, $P < 0.001$). In RS1, 42.5% (±1.4) stem and 0.8% (±0.2) fruit damage was observed compared to 37.2% (±1.0) stem and only 2 fruit damaged (< 0.1%) in RS2. Differences in fruit and stem damage between varieties were most evident within the interplanted Ron's Seedling and Lewis block (Fig 4). Ron's Seedling stem damage was 12 times greater than that observed on Lewis stems ($U = 19972$, $Z = -17.4$, $P < 0.001$). Furthermore, Lewis fruit damage was 1.7% less than that observed in Ron's Seedling fruit ($U = 61128$, $Z = 3.2$, $P = 0.002$).

Differences in damage type were also observed within varieties (Fig 4). In Ron's Seedling, stem damage was on average 11 times higher than fruit damage; Sweet Georgia fruit damage was twice that of stem damage and Lapin fruit damage two times higher than stem damage. No significant difference was observed between fruit and stem damage in Lewis trees ($Z = 1.5$, $P = 0.14$).

When incorporating the number of earwigs found within the cherry bunches and variety into the GLM, Ron's Seedling stems were found to be 40 times more likely to be damaged when earwigs were present compared to Lewis stems whereas Lewis fruit was twice as likely to be damaged as Ron's Seedling fruit (Table S2 for all odds ratios). Similarly, in the Huon Valley, Sweet Georgia fruit were shown to be 4.5 times more likely to be damaged than Lapin fruit and Sweet Georgia stems 5 times more likely to be damaged than Lapin stems. Overall, Sweet Georgia fruit and Ron's Seedling stems were the most likely to be damaged of the four varieties examined.

Significantly more earwig damage was observed on the main limbs than on side branches (χ^2 = 11.2, df = 2, P = 0.004). In Lapin, neither fruit damage nor stem damage were shown to be influenced by bunch position along the limb (Table 3) or limb's cardinal direction (Table 4) despite recorded differences in cherry bunch size (Table 2) and earwig presence (Fig 4). In RS1 trees, cherry stem damage was not related to either bunch position (Table 3) or limb aspect but fruit damage was related to limb aspect (Table 4) with 1.5% fruit damage on the eastern aspect compared to 0.9% on the southern, 0.4% on the eastern and 0.5% on the northern sides. In RS2, stem damage was not significantly related to bunch position (Table 3) but aspect was related, with more stems damaged on the western side of the tree compared to the other cardinal points (Table 4). The observed gradient in earwig numbers at orchard RS2 correlated with a significant increase in stem damage (χ^2 = 123.7, df = 1, P < 0.001) but not fruit damage (χ^2 = 15.0, df = 17, P = 0.60). Low levels of fruit damage observed at RS2 (n = 2) meant analysis could not be performed.

3.2.2 Can earwig trunk trap numbers be related to cherry damage?

No significant relationship could be ascertained between the total number of earwigs found within the trunk traps at the time of harvest and the level of cherry fruit or stem damage (fruit: $F_{1,3}$ = 0.02, P = 0.90; stem: $F_{1,3}$ = 0.1, P = 0.80) nor the number of male earwigs (fruit: $F_{1,3}$ = 1.6, P = 0.20 stem; $F_{1,3}$ = 0.1, P = 0.74), females (fruit: $F_{1,3}$ = 0.4, P = 0.55; stem: $F_{1,3}$ = 1.2, P = 0.27) juvenile earwigs (fruit: $F_{1,3}$ = 0.3, P = 0.64 stem: $F_{1,3}$ = 1.6, P = 0.43) or the total number of earwigs found within the tree canopies within cherry bunches (χ^2 = 0.6, df = 1, P = 0.45).

4 DISCUSSION

This study demonstrates *F. auricularia* can cause severe economic damage to sweet cherry production with damage exceeding 13% in Lapin, 30% in Sweet Georgia and 39% in Ron's Seedling. Our results also show clear differences in both damage type and damage frequency between cherry varieties and different orchards. In Ron's Seedling, stem damage ranged from 37% to 64%, which was significantly higher than that for all other varieties examined. Although differences between Ron's Seedling damage levels could be attributed to differing earwig population sizes in RS1 and RS2, the differences in fruit and stem damage in the Lewis trees compared to Ron's Seedling trees cannot, as these trees were within the one interplanted block (see Table 1).

The tendency of certain cherry varieties to form high density fruit bunches toward the outermost third of the limb may increase a cherry tree's susceptibility to earwig feeding. This is reflected in more earwigs and a greater proportion of damaged fruit and stems, though not significant in all varieties, being typically found within the outer most third of the tree limbs. The limb extremities increased levels of exposure to sunlight may also lead to fruit of a greater maturity when compared to fruit found within the inner parts of the tree canopy. In the southern hemisphere, it is possible that bunches on the cooler, southern and eastern aspects of the tree would provide better daytime residences and the warmer, sunnier northern and western sides of the tree better food resources. In block RS2, which contained widely spaced trees we did see a greater level of stem damage on the western side of the tree. Likewise, in the Lapin trees more earwigs were found residing in the cherry bunches on the cooler, south-eastern side of the trees where stem damage was marginally higher and a trend towards greater fruit damage was also observed on the western facing limbs.

Whether *F. auricularia*'s aggregation pheromone plays a role in the formation of large earwig aggregations within bunches is remains unknown. However, as the theta estimates indicated that the earwigs were not randomly distributed within the tree canopies, it is plausible that the pheromone does aid in the formation of aggregations within bunches. This could also explain why large earwig numbers were found in some smaller bunches when other neighbouring large bunches contained few to no individuals.

Bunch architecture may also play a critical role in earwig preference of daytime residence and any ensuing damage though this was not explicitly tested. Ron's Seedling appear to produce smaller bunch sizes that have shorter, thicker stems, with a more open bunch structure that may be less favoured by earwigs. This open bunch architecture may also promote the elevated levels of stem damage observed in Ron's Seedling trees which, like fruit damage, reduces the saleability of the fruit due to their not meeting the strict quality standards required by consumers. Similarly, varieties such as Sweet Georgia and Lapin, produce large, dense cherry bunches, appear more favoured by earwigs due their providing suitable daytime residences. The provision of daytime residences within larger fruit bunches appears to create opportunities for daytime feeding to occur and may explain why solitary fruit or small bunches containing few cherries (2-4 fruit) were seldom damaged. However, determining whether the observed damage is occurring within the bunches during daytime sheltering rather than nocturnal foraging may prove difficult as any disturbance within the fruit bunches would most likely disrupt their natural behaviours.

The stems of Ron's Seedling were damaged significantly more than the other varieties examined, irrespective of bunch size. The reason for this strong preference remains unclear as the resulting damage rarely penetrated the epidermal layer into the stem's vascular tissues, which would contain greater quantities of water, nutrients and carbohydrates. It seems unlikely that the earwigs are aiming to glean greater nutritional uptake from stem consumption although it remains plausible that epidermal layer of Ron's Seedling stems is more nutritious compared to the stems of other varieties. The increased susceptibility of Sweet Georgia cherries to earwig damage compared to Lapin cherries also was not well explained by the physical characters we examined. Sweet Georgia was developed from a Lapin sport causing later fruit ripening approximately two weeks after its parent variety.[27] This mutation appears to have little effect on the bunch size or bunch architecture or physical characteristics of the fruit including fruit firmness[33], but other characters not examined may differ. Indeed, several studies have demonstrated that different varieties show differing sugar, phenolic or organic acid compositions[34, 35] and that the concentration of these nutrients increase during maturation[36] when the majority of damage occurs.

The age of the cherry tree may also be a complicating factor when monitoring earwig populations with traps placed on the tree trunk. Earwigs were frequently observed residing in cracks within the older tree trunks rather than in open fruit bunches or within the cardboard roll traps, which are often used for earwig monitoring in orchards.[7, 8, 37, 38] These cracks may also be impregnated with relatively large quantities of aggregation pheromone, which enhances cracks as their chosen daytime residences. If action thresholds can be developed for earwigs in sweet cherry an alternative method of earwig population monitoring will be required, particularly in older trees. These cracks would also create an additional issue when aiming to chemically control earwigs in old trees as insecticide penetration into these spaces is difficult. Trunk trap earwig numbers at the time of harvest were not found to be a useful indicator of cherry damage during this study. However, closer monitoring of earwig population dynamics throughout the cherry growing season may indicate a monitoring period suitable for the development of action (spray) thresholds for IPM cherry production. Furthermore, any model would need to account for cultivar and average fruit bunch size or crop load if it is to provide accurate damage predictions.

This study demonstrates that earwigs can cause severe economic impacts to sweet cherry production and that the nature of this impact significantly differs between the varieties examined with Lapin the least prone to earwig damage. The damage type and severity are strongly influenced by numerous factors including bunch size, and bunch position, limb orientation and possibly to a lesser extent, orchard design. However, just why these observed differences occur warrants further investigation if the financial and environmental impacts of earwigs in sweet cherry production are to be minimised, which may impact on their usefulness as biological control agents in cherries for pestiferous species such as spotted wind drosophila as has been postulated in previous studies.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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Figure 1. Relationship between the number of *Forficula auricularia* observed within cherry bunches and cherry bunch size in four varieties of sweet cherry and the predicted ZIP models. Earwigs within Lapin and Sweet Georgia cherries were observed in an organic orchard in the Huon Valley, Tasmania, Lewis and Ron's Seedling cherries were observed in a cherry orchard in Young, NSW.

Figure 2. Proportion of total *Forficula auricularia* found within cherry bunches in Lapin cherry tree canopies (n = 20) by limb aspect (N, S, E and W) and bunch position along the limb showing a significant preference for bunches in the southern and eastern aspect of the tree and northern most terminal fruit bunches (Logistic Regression, $P = 0.03$).

Figure 3. *Forficula auricularia* aggregation parameters estimates (θ ± 90% CI) by (a) cherry bunch sizes and (b) earwigs per bunch where > 1 earwigs were present within the bunch. Theta (θ) is the shape parameter of the Negative Binomial distribution. Where distributions approaching zero indicate earwig aggregation (negative binomial distribution) and estimates further from zero ($\theta \rightarrow \infty$) indicate a randomly dispersed earwig population throughout the tree canopy (Poisson distribution). Dotted lines indicate CI.

Figure 4. Percentage earwig cherry fruit and stem damage (± SE) from four varieties of Sweet cherry. Asterisks indicate significant difference between damage types within varieties (Mann Whitney U test, $P < 0.001$.

Table 1. Experimental site characteristics for the *Forficula auricularia* exclusion and cherry bunch size experiments.

	Experimental Block				
	RS1	RS2	Lapin	RS/LW	Sweet Georgia
Experiment	Exclusion	Exclusion	Exclusion/Bunch size	Bunch size	Bunch size
Trees sampled	20	20	20	40	20
Data collected	16th Nov 11	15th Nov 11	9th Jan 12	17th Jan 11	14th Jan 12
State	NSW	NSW	TAS	NSW	TAS
Planting date	1999	1996	2002	1983/1988	2006
Row orientation	N/S	E/W	NW/SE	E/W	NW/SE
Row spacing (m)	5.50	6.10	3.50	6.70	3.50
Tree spacing (m)	2.30	3.80	1.25	3.35	1.25
Irrigation	drip	nil	drip	nil	drip
Management type	conventional	conventional	organic	conventional	organic
Ground cover	mulch	mulch	grass	mulch	grass
Bird netting	no	no	yes	no	yes
Rain covers	yes	no	no	no	no

Table 2. Mean bunch size (SD) of sweet cherries from the four cardinal points and the inner, middle and terminal thirds of the limbs. Cherry number: RS1 n = 1314, RS2 n= 1396 and Lapin n = 763.

		Cardinal direction			
Block	**Bunch position**	**North**	**South**	**East**	**West**
RS1	Inner	3.37 (2.11)	3.58 (3.58)	4.13 (2.75)	3.43 (2.43)
	Middle	3.69 (2.59)	4.08 (2.41)	4.58 (3.22)	3.78 (2.95)
	Terminal	3.42 (2.95)	3.60 (3.30)	4.88 (4.61)	3.96 (3.61)
RS2	Inner	5.96 (5.82)	4.70 (3.68)	5.51 (3.76)	5.01 (3.76)
	Middle	5.24 (5.43)	5.05 (5.55)	5.63 (5.11)	6.17 (6.43)
	Terminal	5.40 (7.14)	5.89 (10.36)	9.48 (13.74)	6.05 (9.54)
Lapin	Inner	4.48 (2.79)	5.98 (6.76)	6.89 (5.55)	5.63 (4.40)
	Middle	5.65 (5.35)	7.40 (6.03)	8.85 (10.04)	5.87 (4.85)
	Terminal	7.50 (8.65)	9.44 (11.31)	9.04 (8.29)	10.31 (10.48)

Table 3. Percentage fruit and stem damage (SE) at three bunch positions along tree inner, middle and outer thirds of the limb in two Ron's Seedling and one Lapin cherry block during the 2011/12 season. N/A indicates statistical analysis could not be performed due to an insufficient number of damaged cherries.

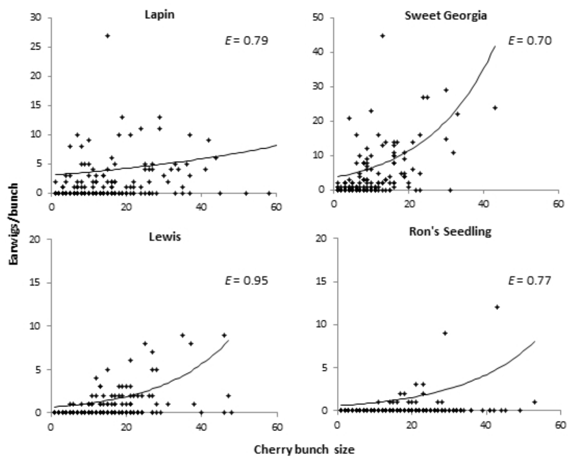
		Bunch position on limb							
		Fruit damage (%)				Stem damage (%)			
Block	**n**	Inner	Middle	Terminal	*P value*	Inner	Middle	Terminal	*P value*
RS1	5251	0.7 (0.2)	0.7 (0.2)	0.9 (0.2)	0.7	42.7 (1.3)	41.5 (1.1)	43.0 (1.2)	0.6
RS2	8317	0.0 -	0.0 -	0.0 -	N/A	33.9 (1.0)	34.9 (0.9)	40.0 (0.9)	0.1

Lapin	5485	5.6 (0.6)	6.1 (0.6)	7.6 (0.6)	0.06	2.1 (0.4)	1.5 (0.3)	2.4 (0.3)	0.1

Table 4. Percentage fruit and stem damage (SE) in tree limbs at the four cardinal points observed in two Ron's Seedling and one Lapin cherry block during the 2011/12 season. Bold type indicates significant difference at < 0.05. N/A indicates statistical analysis could not be performed due to an insufficient number of damaged cherries.

		Limb aspect									
		Fruit damage (%)					**Stem damage (%)**				
Block	**n**	N	S	E	W	*P value*	N	S	E	W	*P value*

RS1	5251	0.5 (0.2)	0.9 (0.3)	1.3 (0.3)	0.4 (0.2)	**0.01**	49.2 (1.5)	42.1 (1.4)	37.4 (1.3)	41.3 (1.3)	0.8
RS2	8317	0.0 -	0.0 -	0.0 -	0.0 -	N/A	36.7 (1.1)	32.9 (1.1)	34.3 (1.0)	45.0 (1.1)	**0.04**
Lapin	5485	6.9 (0.7)	6.6 (0.7)	5.8 (0.6)	7.1 (0.7)	0.5	1.8 (0.4)	2.6 (0.4)	1.7 (0.3)	1.9 (0.4)	**0.05**



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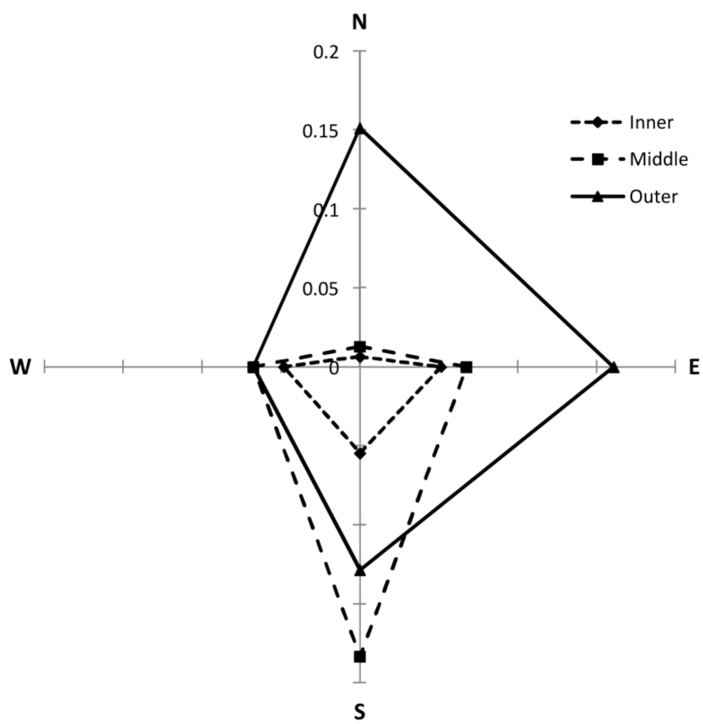

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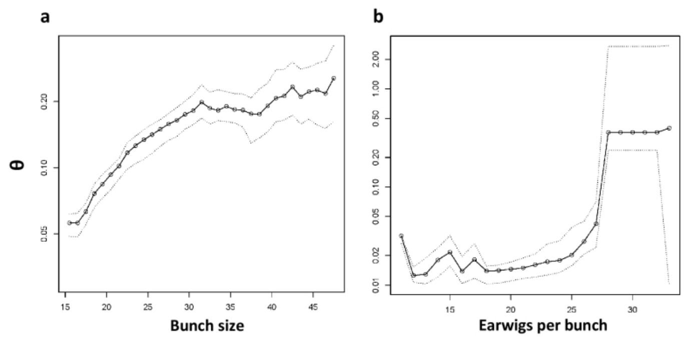

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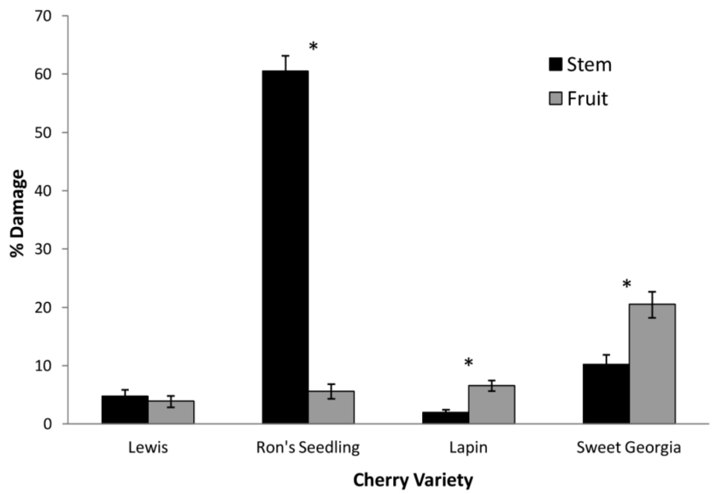

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